Challenges of High Field Magnets

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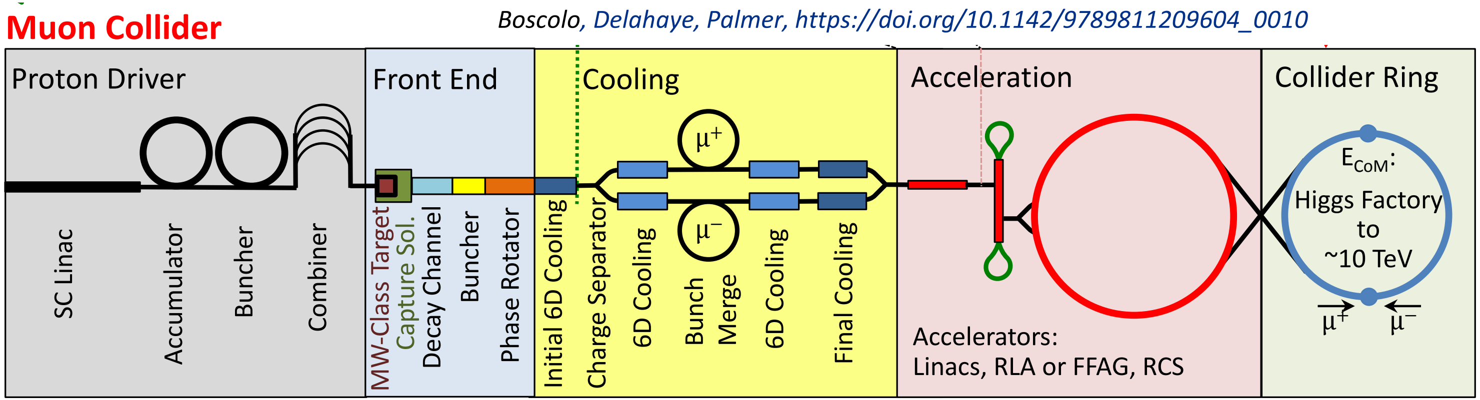
Workshop on Muon Driven Colliders

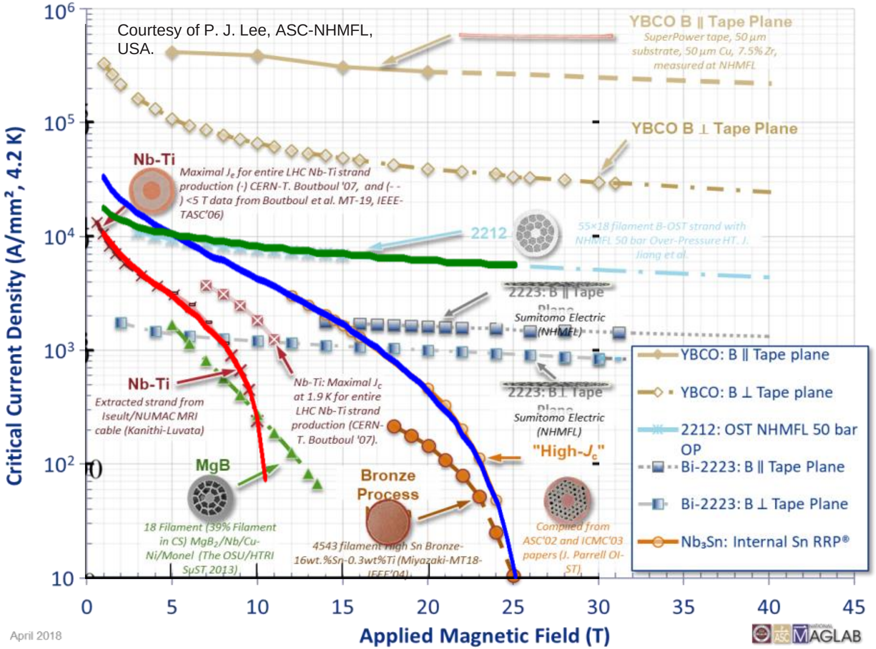
26-27 January 2022

Outline



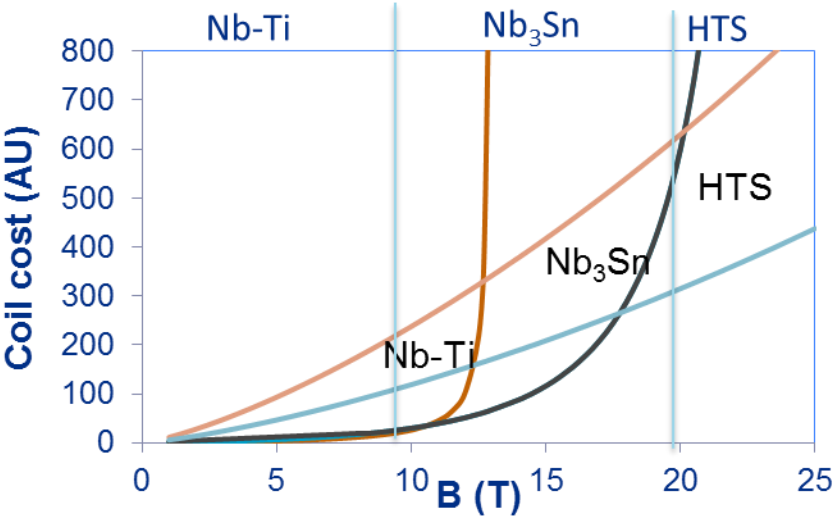
- Introduction
- Practical superconductors
- MC key systems and magnets
  - Front End, Cooling, Acceleration, Storage Ring and Interaction Regions
- High field magnet challenges
- Summary

Practical superconductors



Coil cost ~ coil area x SC cost

Relative SC cost: Nb-Ti/Nb_3Sn/HTS = 1/5/20(10)



Practical SC materials for SC magnets include *appropriate critical parameters, their reproducibility in long lengths, mass production and affordable cost*.

Boundaries are not fixed, they depend on superconductor and magnet technology costs.

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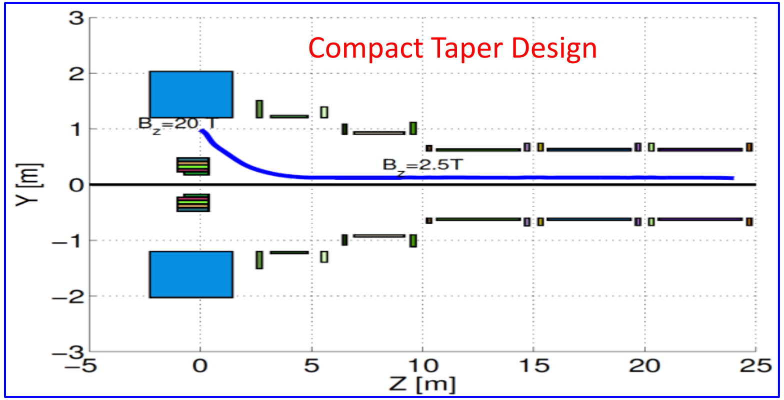
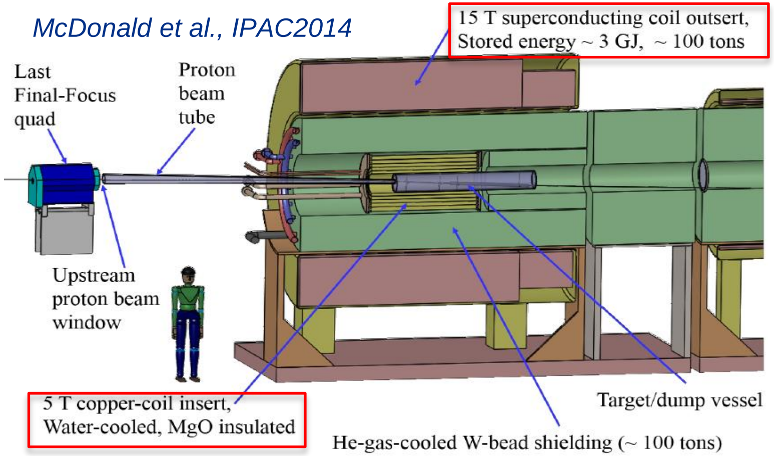
Front End - Target & Capture Magnets

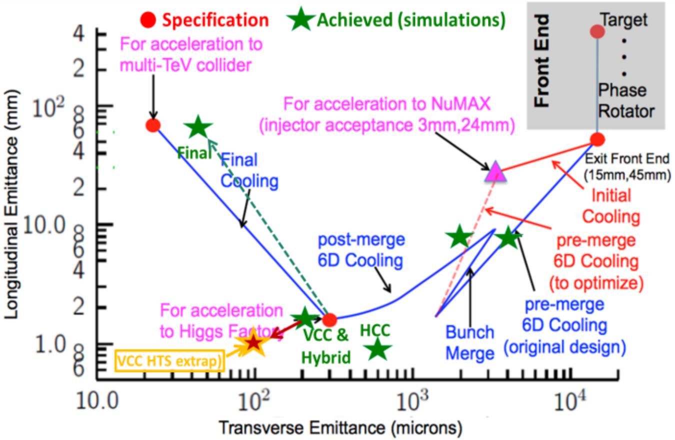
- System functions
  - Produce muons from protons on target
  - Prepare muon beams for the ionization cooling
- 20 T Capture Solenoid
  - 15T SC outsert: ~2 m ID, 3 GJ, 100 t
  - 5 T Cu insert: ~0.3 m ID
- Solenoid decay channel
  - taper from 20 T to ~2.5 T
- Technology
  - Detector or fusion solenoids
    - CMS: 6 m ID, 4 T, 2.6 GJ
    - ITER CS: 0.6 m ID,13 T, 6.4 GJ
- Issues and challenges:
  - Severe radiation environment
  - Possibility of using HTS for the insert
  - Large aperture-high field for Nb_3Sn
- Continue DS to identify issues and develop solutions



McDonald et al., IPAC2014

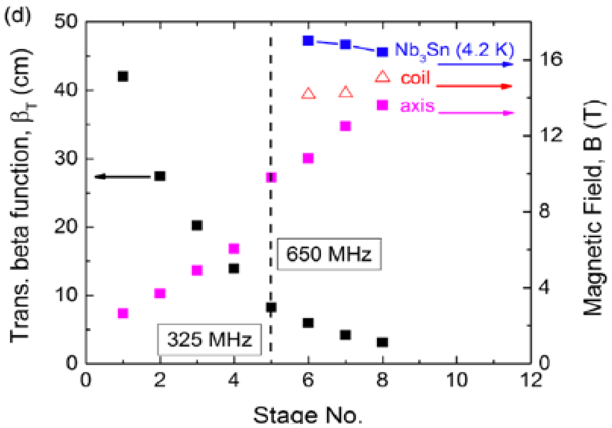


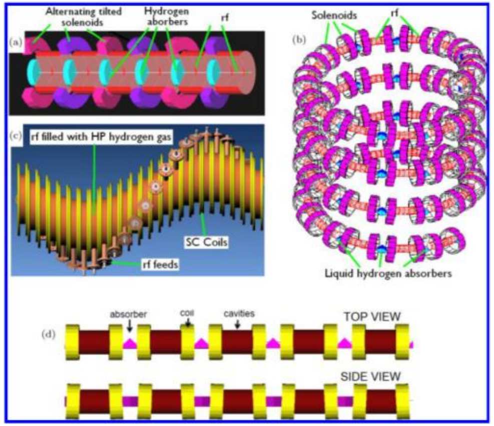
Muon Cooling Systems



Muon Cooling

- Energy dissipation in materials with RF re-acceleration
- Operation in a solenoidal field
- Aperture reduces from ~1m to 50 mm





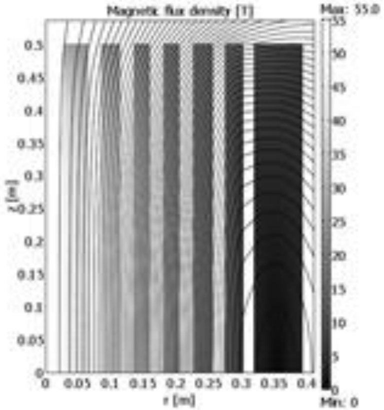
6D cooling

(a) HFOFO snake
(b) Guggenheim RFOFO
(c) helical cooling channel (shown without a large outer straight solenoid)
(d) rectilinear RFOFO

- B_{op} range from 5 to 20 T
- Aperture range ~50-10 cm
- HTS magnets in 6D Cooling

Final Cooling:

- RF cavities between solenoids
- Bores ID of ~50 mm
- Cooling performance is proportional to B
- Ideal range 50-60 T
  - >30T acceptable

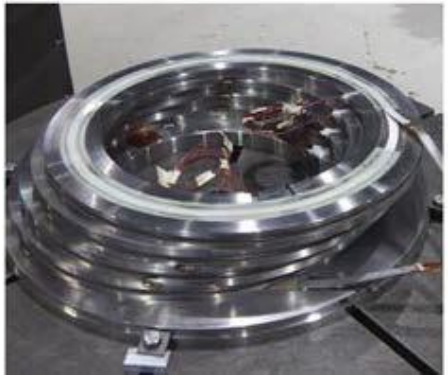


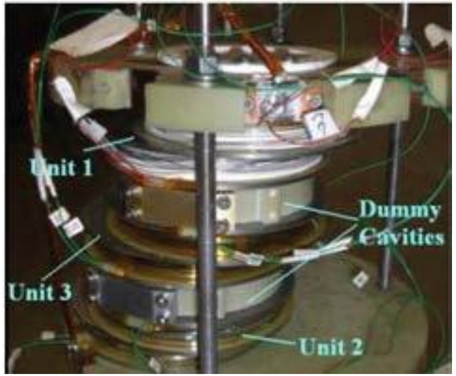
V.V. Kashikhin et al., MT

Cooling channel technology development

V. S. Kashikhin et al.TAS 2007

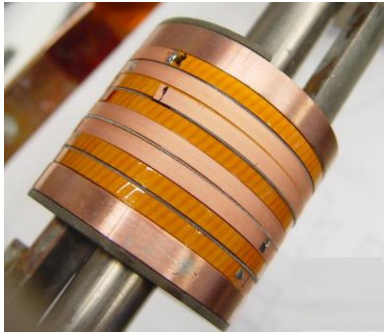
M. Yu et al., FERMILAB-CONF-11-265



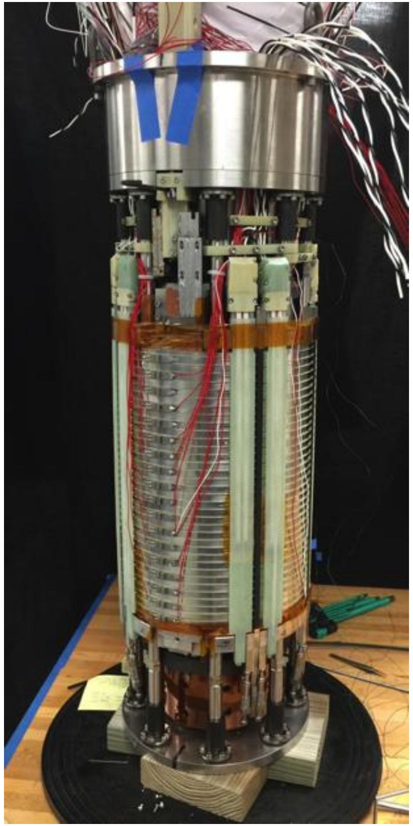


400-mm 4 T Nb-Ti 4-coil and 50-mm YBCO HS models

V. Lombardo et al., TAS 2010



4 Double Pancake
YBCO insert coils



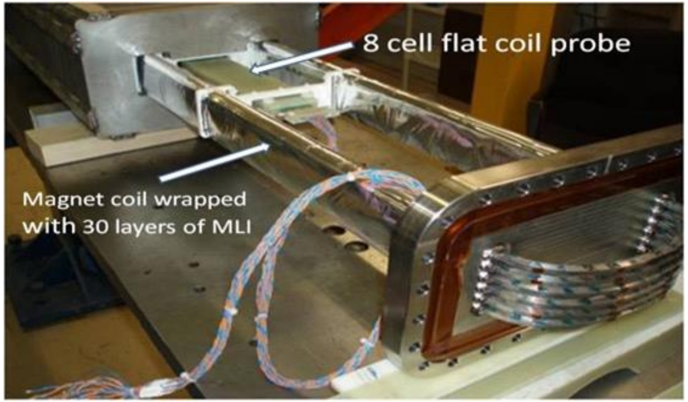
World Record 32 T
LTS-HTS Hybrid
Solenoid (NHFML)

Issues and challenges:

– High fields
– Possibility of using HTS for the insert
– Large-aperture high-field for Nb_3Sn
– Use of accelerator magnet technologies

Acceleration: Fast Ramping HTS Magnets

- Present baseline - Rapid Cycling Synchrotron
  - magnets operating at ~400 Hz with Bmax>1.5 T
- dB/dt = 289 T/s with field amplitude ~0.5 T has been demonstrated using HTS dipole model (H. Piekarz, 2021)
- Next step – increase B_{max} and dB/dt, study magnet and system limits
- Higher field amplitude – iron free (warm iron) designs



H. Piekarz et al., MT-27

1 – Magnet, 2- Current leads, 3- Power supply, 4 – Control electronics, 5- LHe lines

For the 10 T DC dipoles - see section SR and IR magnets below

Muon Collider SR and IR

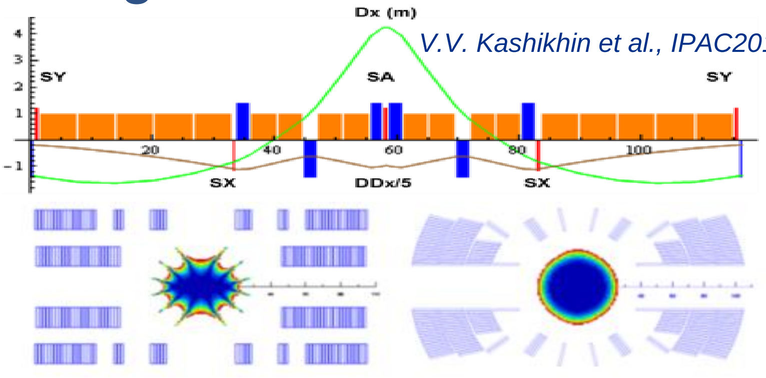
- MAP Optics Designs for
  - 1.5 TeV CoM
  - 3.0 TeV CoM => 6.0 TeV CoM
  - Higgs Factory (125 GeV CoM)
- Magnet Characteristics
  - Higher B is better, MC luminosity $\propto B_{dipole}$
  - Large apertures to accommodate thick shielding around beam
  - IR combined function magnets to mitigate ν radiation

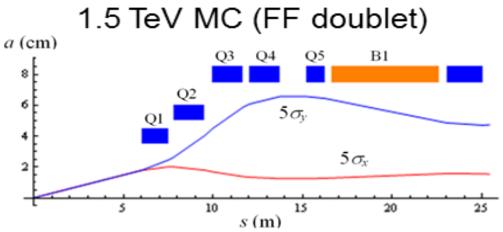
- High fields required for MC call for advanced accelerator magnet technologies beyond traditional Nb-Ti magnets limited to B_{op}~8 T
- Nb_3Sn magnets – *baseline approach*
  - B_{nom}=10 T
  - large operation margin >20%
  - mature magnet technology (B_{op}<12 T) thanks to GARD and LARP work during past two decades
- Conductor – *present technology limit*
  - 1 mm high-J_c Nb_3Sn strand
  - wide 40-42 strand Rutherford cables

1.5 TeV MC: Arc and IR Magnets

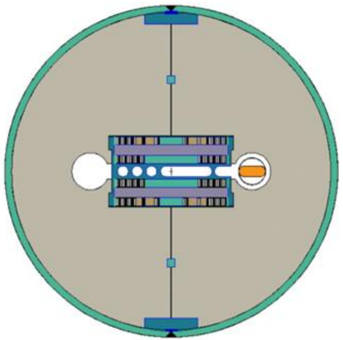
- Arc magnets
  - 20 mm × 10 mm beam aperture
  - Open mid-plane 10T D and large-aperture 200 T/m Q
    - relatively low operation margin ~12%
    - good field quality only in ~30% of coil aperture
    - large dynamic heat load in D ~25 W/m (~5% level)
- IR magnets
  - B_{op}=8 T (D), B_{op}~11 T (Q)
  - B_{des}=14-15 T with 2-layer coils
  - 20-30% (Q) and 45% (D) operation margin
- W masks and inner absorbers

V.V. Kashikhin et al., IPAC2012

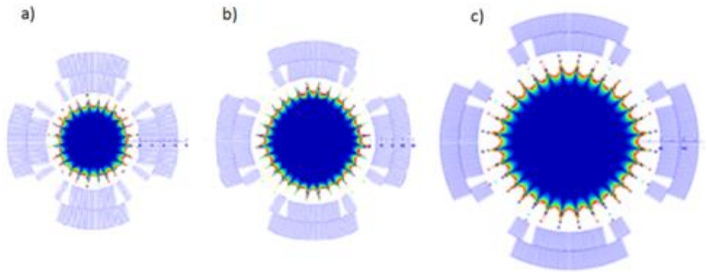




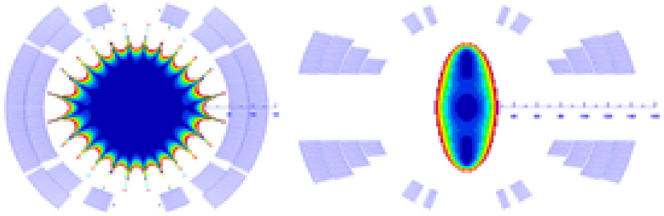
Novitski et al., TAS 2011



Open mid-plane in D does not work well



Q1, 80 mm Q2, 110 mm Q3-5, 160 mm



B1, 160 mm

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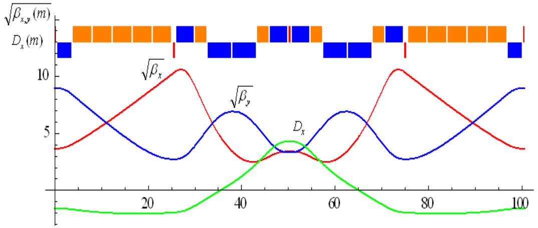
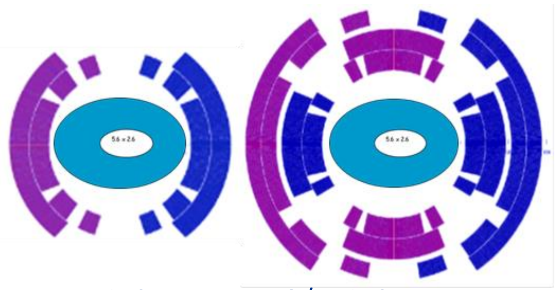
3 TeV MC: Arc and IR Magnets

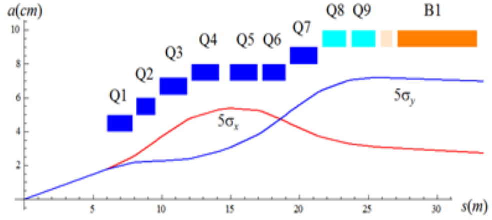
- Arc magnets
  - 150 mm aperture D and combined Q/D
  - Elliptical liner with shifted 56 mm × 26 mm bore
  - B_{op}=10.4 T with ~30% margin at 4.5 K => 2-layer coils
  - B_{op}~8-9T and G_{op}~80T/m with ~20% margin (B_{coil} ~18 T) at 4.5 K => nested Q/D with 4-layer coils
- IR magnets
  - B_{op}=8 T (D), B_{op}~11 T (Q)
  - Aperture 80-180 mm
  - B_{des}=14-15 T with 2-layer coils
  - 20-30% (Q) and 45% (D) operation margin
- Tungsten masks and inner absorbers

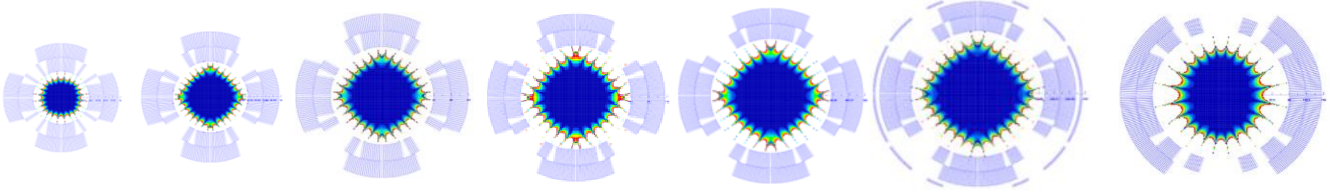




D, 150 mm   Q/D, 150 mm

3 TeV MC (FF triplet)

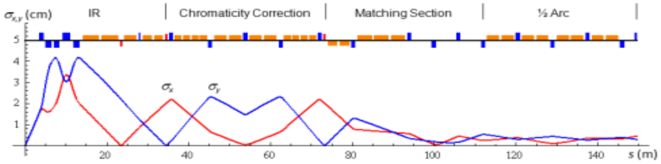


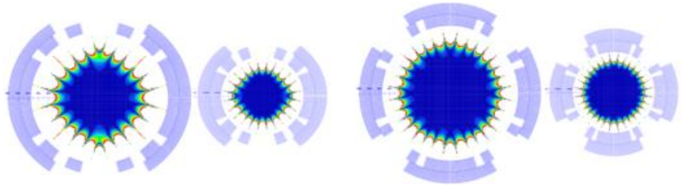


Q1, 80 mm   Q2, 100 mm   Q3, 125 mm   Q4-6,140 mm   Q7, 160 mm   Q8-9, 180 mm   B1, 180 mm

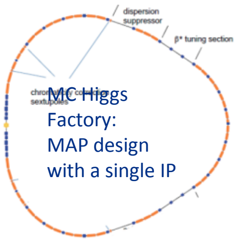
125 GeV HF: CCS, MS, Arc and IR Magnets

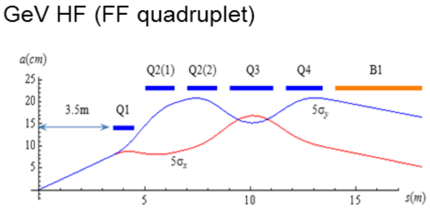
- CCS, MS and Arc magnets
  - coil ID 160 mm (Arc) and 270 mm (MS, CCS)
  - B_{op}=10 T with ~30% margin at 4.5 K (B_{max}~14 T) with *2-layer D coils*
  - G_{op}~36 T/m with ~60-80% margin at 4.5 K (max B_{coil} ~15 T) with *2-layer Q coils*
- IR magnets
  - IR magnet aperture is large 320-500 mm (!)
  - B_{des}~17-18 T requires *6-layer coils* for quench protection and to limit maximum coil stress
  - 20-50% operation margin in IR magnets
- W masks and inner absorbers

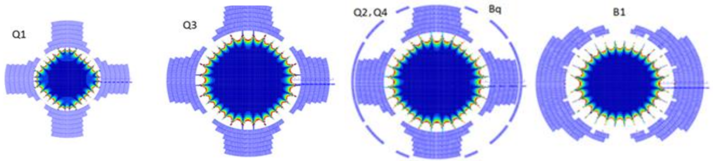




D1, 270 mm D2, 160 mm Q1, 270 mm Q2, 160 mm



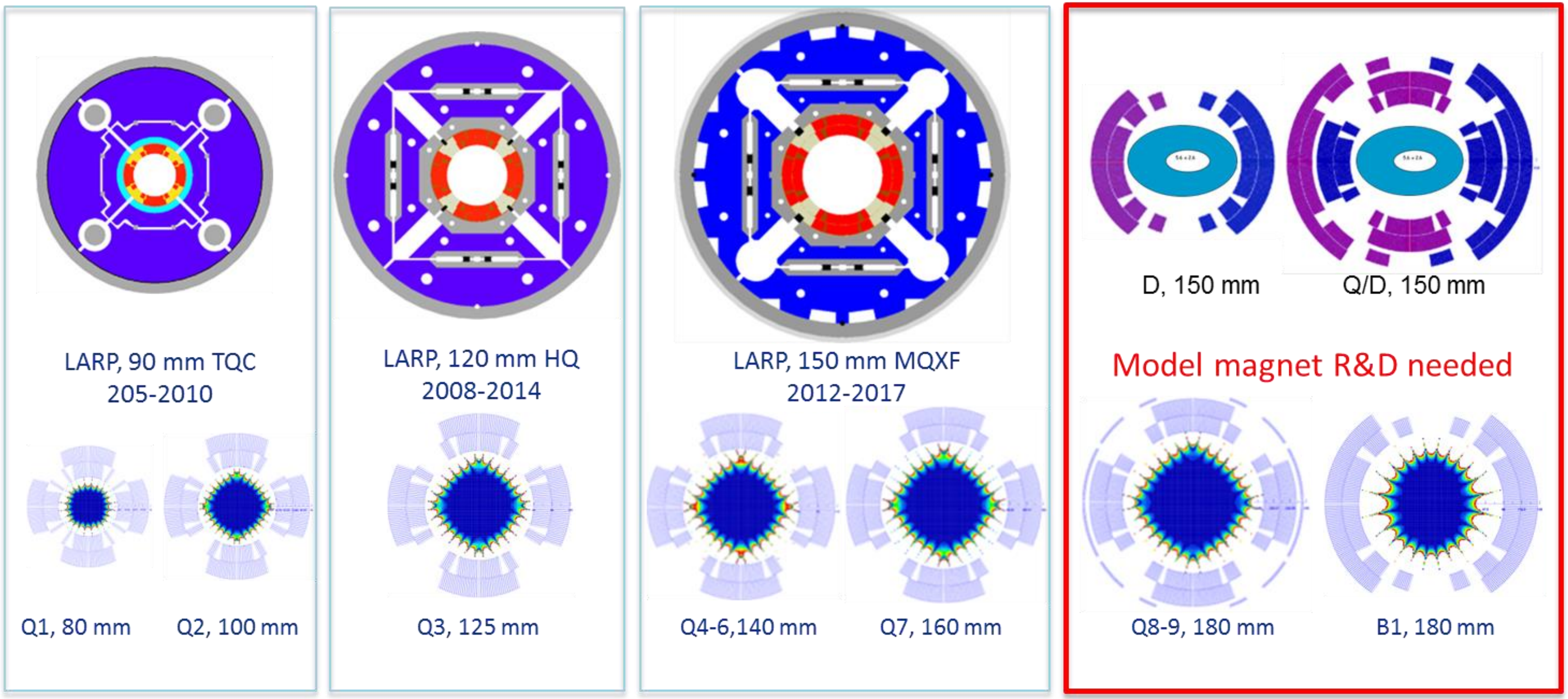




Q1, 320 mm Q3, 500 mm Q2,4, 500 mm B1, 500 mm

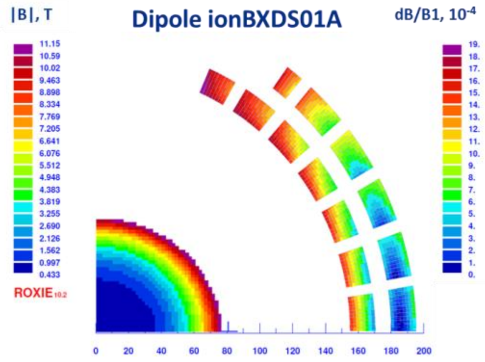
N.V. Mokhov et al., ArXiv, JINST, 2018

Nb_3Sn Magnet model R&D

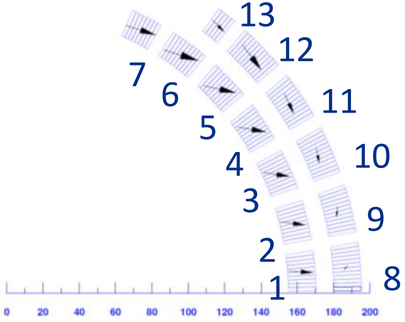


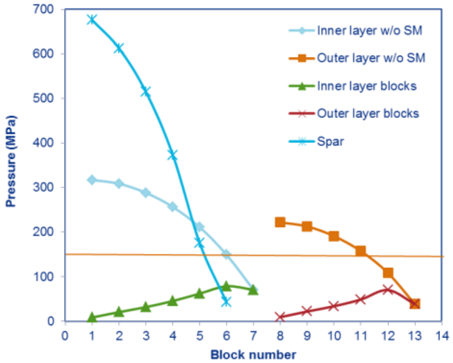
- R&D issues: mechanical structure, quench performance, field quality, quench protection, etc.

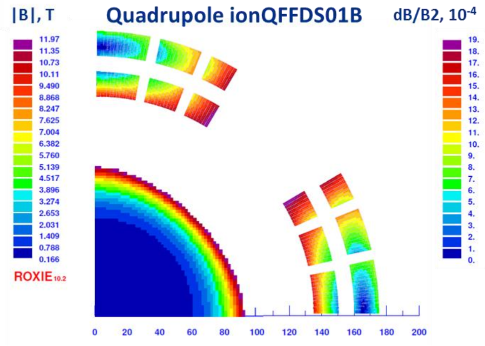
Stress Management needed



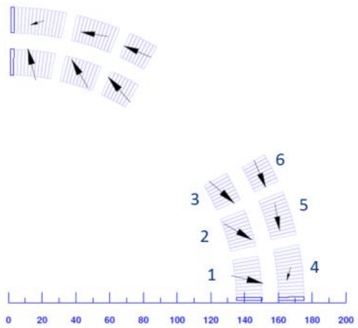
Coil ID, mm	310
Iron yoke ID, mm	200
Coil current, kA	14.5
Bore field $B0_{max}$, T	9.48
Coil field B_{max}, T	11.47
Load line margin, %	72.6
Temp. margin @1.9K, K	6.02
Stored energy @B_{max}, MJ/m	1.21

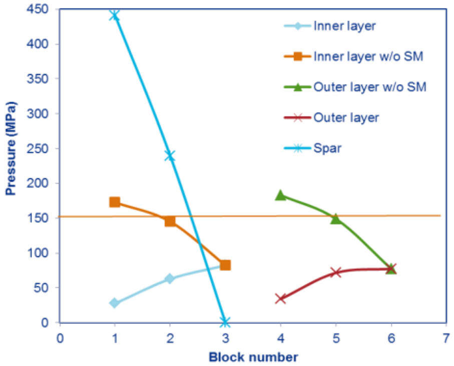






Coil ID, mm	270
Iron yoke ID, mm	180
Coil current, kA	17.5
Field gradient G_{max}, T/m	74.39
Coil field B_{max}, T	11.98
Load line margin, %	80.3
Temp. margin @1.9K, K	4.75
Stored energy @G_{max}, MJ/m	2.90





- ***Stress management on the coil level is critical***
  - synergy with MDP on SMCT technology development and demonstration

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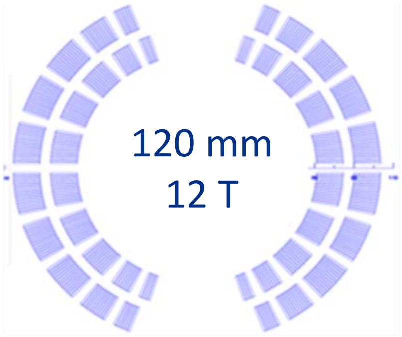
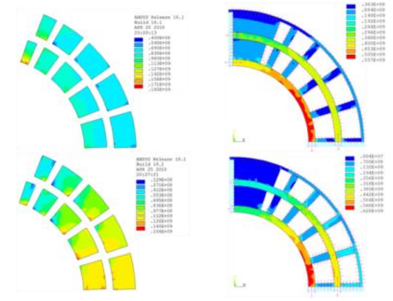
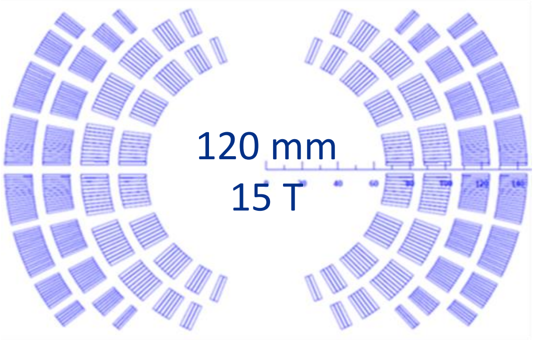
Stress Management for high-field large-aperture magnets

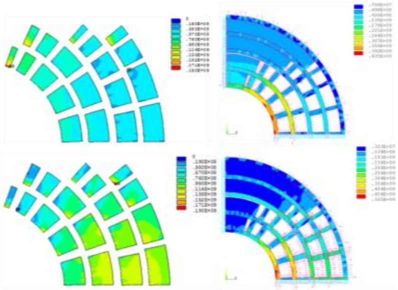
Design studies





Equivalent stress (Pa) in the coil (left) and the coil support support structure (right) of Design 1 after cool-down (top) and at 11 T bore field (bottom).

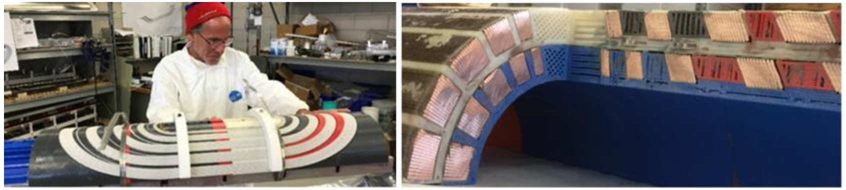




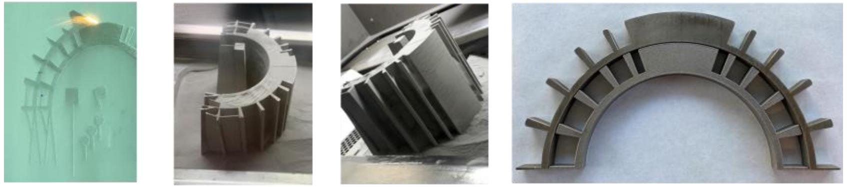
Equivalent stress (Pa) in the coil (left) and the coil support support structure (right) of Design 2 after cool-down (top) and at 15 T bore field (bottom).

A.V. Zlobin et al, IPAC2018.

Technology development



Coil practice winding and impregnation



Coil mandrel production by additive manufacturing

3D printed parts for the coil mandrel : plastic-left and 316stainless steel - right

I. Novitski et al, MT-27.

- US-MDP 120 mm ID 12-15 T dipole demonstrators with Nb_3Sn SMCT coils
  - results in 3-4 years

Higher Field Magnets

- Higher fields in MC SR => higher *L* or lower Proton Driver power
- Magnet target parameters:
  - B_{op}=15-20 T (Bmax~14.5 T Fresca2 and MDPCT1, aperture 60-100 mm)
  - 20% margin => B_{des}=18-25 T !!!
- 15-20 T magnet issues
  - Large stored energy and Lorentz forces => Quench protection and stress management
  - Cost ~ *coil width*)
- Magnet R&D directions
  - Increase Nb_3Sn and HTS conductor J_E
  - Develop high-current Nb_3Sn and HTS cables
  - Solve stress management and quench protection problems
  - Demonstrate quench performance and field quality for large-aperture Nb_3Sn and HTS magnets

Summary

- Front end: 20 T solenoid – detector or fusion technology, design studies
- Magnet cooling – 50 T solenoid
- Acceleration – fast cycling dipole, increase B and f

HTS technology

- Magnet studies for 0.125, 1.5 and 3 TeV MC SR are complete by MAP
  - SR and IR magnets for 6 TeV machine – *small extension of the 3 TeV concepts*
- 10 T Nb_3Sn magnets – *MAP baseline approach*
  - magnet technology is *available* from LARP-HL-LHC and MDP
  - *focused R&D* for large-aperture Nb_3Sn dipoles and nested Q/D
- Higher field magnets
  - 15 T Nb_3Sn magnets with coil ID~20(40) cm, B_{des}~18 T – *new class of Nb_3Sn accelerator magnets with stress management*
  - 20 T HTS/LTS magnets (10 T HTS insert) with ~20 cm bore, B_{des}>25 T – *new magnet technology based on HTS => significant R&D effort is needed!!!*